Modeling and Interpretation of Electromagnetic data for mature oil fields monitoring

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Abstract

In this paper we present the results of direct modeling and statistical inversion of frequency domain electromagnetic data acquired in 2005 over a mature oil field. The direct model uses finite elements to solve the Maxwell equations and establish the relation of the apparent resistivity and induced polarization with depth, while well resistivity logs were used as guides to the 1D inversion scheme, which used the VFSA algorithm. The results of the inversion are then used to model the resistivity curves in wells not used in the inversion as a validation of the process.

Introduction

In the past few years the use of the Electromagnetic Method has been extended to the oil industry, particularly as a tool for monitoring water injection in mature oil fields and in shallow exploration. A survey conducted in 2005 gathered enough EM data to perform a series of studies, including the direct and inverse modeling of the problem. We used finite elements to solve the Maxwell Equations and use this as input for direct modeling and resistivity well logs as guides to the non-linear, statistical inversion process. Through the measurements made in the field we were able to derive relations of the apparent resistivity and induced polarization with the eletric e magnetic fields, which was possible thanks to the equipment developed by LENEP/UENF, headed by Prof. Carlos Alberto Dias.

The survey layout featured several transmitter and receivers positions, reversing them from time to time and with separations ranging from 400m to 2100m. For each fixed transmitter and receiver position 45 useful frequencies were induced (from 1.125Hz to 10473Hz). The field data was initially filtered for ambient noise and notches, but other problems were present, like topography, which was not accounted for. Despite that, the correlation of the field data with the model was acceptable.

The acquired EM data was comprised of three electric field components (Ex, Ey and Ez) and three magnetic fields components (Hx, Hy and Hz), but for our purposes we only used the magnetic ones. This was done because the direct modeling targeted the mutual impedance, a physical quantity representing the ratio of vertical and horizontal magnetic fields, following the studies made by Sato (Sato 1979). The finite elements program used to solve the equations for those fields was provided by the Scripps Institute of Oceanography, and solves for a 2.5D problem, i.e., the source is 3D but the medium is 2D. We then compare the results of this modeling with the field data.

The inversion was carried using a statistical non-linear method to estimate the desired parameters, the Very Fast Simulated Annealing, proposed by Stoffa (Stoffa 1996). The model assumes that the electrical conductivity does not change abruptly in space, and in this case we considered that this variation occurred in a layer model, which means that the function was not defined in every point of the medium, but in blocks, simplifying the model building. The algorithm used well log curves as *a priori* information, and then used again in other wells as validation of the process.

Solving the direct Model Equations

As described by Ward (1988), the Maxwell equations in the frequency domain in the presence of a source can be writen as:

$$\nabla \times \vec{E} + \hat{z}\vec{H} = -J_m^s \tag{1}$$

$$\nabla \times \vec{H} - \hat{y}\vec{E} = J_e^s \tag{2}$$

where $\hat{z} = i\mu\omega$, $\hat{y} = \sigma + i\varepsilon\omega$, J_m e J_e stand for the magnetic and electric source, respectively. Let us consider now that the fields E and H can be writen as:

$$\vec{E} = \vec{E}_m + \vec{E}_e \tag{3}$$

$$\vec{H} = \vec{H}_m + \vec{H}_e \tag{4}$$

meaning that these fields have could have contributions from eletric and magnetic sources.Hence, for $[E_m, H_m]$, we assume that $J_e^s = 0$, whilst for $[E_e, H_e]$ we assume $J_m^s = 0$. By making these assumptions it is possible to show that:

$$\vec{E}_m \equiv -\nabla \times \vec{F} \tag{5}$$

$$\vec{H}_e \equiv \nabla \times \vec{A} \tag{6}$$

$$\vec{H}_m = -\hat{y}F - \nabla U \tag{7}$$

$$\vec{E}_e = -\hat{z}A - \nabla V \tag{8}$$

with F and A being the Schelkunoff potentials and U and V arbitrary scalar functions. If we consider a point source in space we can solve the Maxwell equations for F, and from that obtain the radial and vertical magnetic fields as:

$$H_\rho = \frac{m}{4\pi}\int_0^\infty [e^{-u_0 z} - r_{te}e^{u_0 z}]\lambda^2 J_1(\lambda\rho)d\lambda \tag{9}$$

$$H_z = \frac{m}{4\pi}\int_0^\infty [e^{-u_0 z} - r_{te}e^{u_0 z}]\frac{\lambda^3}{u_0} J_0(\lambda\rho)d\lambda \tag{10}$$

and once we calculate these fields we can obtain the mutual impedance. Besides this method, we applied finite elements to calculate the magnetic fields for a layered medium, follwing the equations in Ward (1988) with aid of the MARE2DCSEM tool provided by the Scripps INstitute of Oceanography.

The inversion process

In this work we chose to apply a statistical for the inversion process, the Very Fast Simulated Annelaing (VFSA), which causes small perturbations in the model space based in a parameter called temperature, and at each interaction a new solution is calculated based on these new, perturbed parameters. By calculating the energy of the error, we can get as close as we want to the desired solution. The error is defined as:

$$E = \frac{1}{N}\sum_{i=1}^{N}[Z_i - z_i(m)]^2 \quad (11)$$

with Z being the real data and z the calculated data. Our first test, as a validation process, was to use a analitical equation as the forward model to the real data. We chose the Cole-Cole model for the sake of simplicity, which is writen as (Mansoor 2007):

$$\sigma^*(\omega) = \sigma_0[1 + m(\frac{(i\omega\tau)^c}{1+(i\omega\tau)^c(1-m)}] \quad (12)$$

This equation describes the electrical conductivity for a layered medium as a function of frequency, chargeability(m) and relaxation time. However, this equation did not fit well with most of the data, so we had to use the finite element method as the forward model, and even tough we still modeled the medium as a layered one, the freedom offered by the finite element method meant a much better fit to the field data.

The inversion was carried out for each dataset, .representing the mutual impedance as a function of frequency and source-receiver separation. The algorithm then perturbed slightly the parameters and a new value for the impedance was calculated. The initial values for resistivity were derived from well logs, and at each interation this value had to be respected at a certain degree.

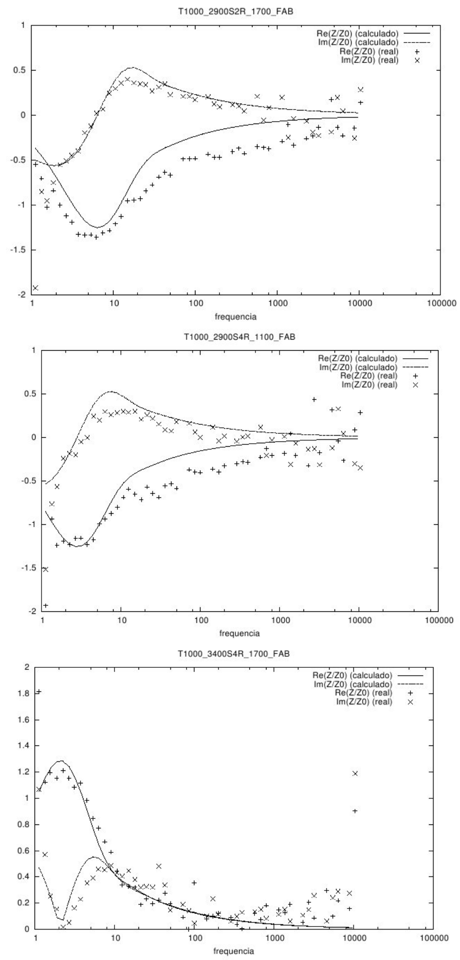

Figure 1: Results from the inversion process compared to the real data. Both real and imaginary components are drawn for different source and receiver separations. Notice that the higher are noisier and have a worse fit.

Examples and Results

We first show the results of the inversion model applied to the real data. In figures 1, 2 and 3 the curves represent the mutual impedance calculated using the forward and inversion processes compared to the field data. For the most of the experiments the results were very good, despite the noise present in the data, altough for the higher frequencies the concordance tends to be poorer. This means that a layered medium was enough to model the propagation of the fields.

Figures 4 and 5 show the result for the calculation of electrical conductivity compared to the well logs of the area. The 1D resistivity have a general good fit, but the calculated resistivity seems to change for the reservoir layer at depths smaller than those seen in the well logs. This represents the 4D effect, since the water injection has caused a pull up effect in the oil water interface .

Summary, Comments and Conclusions

This paper presents the results of a full modeling/inversion process and validates the results with experimental data, as curves of mutual impedance, and with comparisons of calculated electrical resistivity versus well log data. The results are encouraging and signal in the direction of a better interpretation of the effects of water and steam injection as a tool for enhanced oil recovery in mature fields. Improving the model for both forward and inverse processes, giving a better treatment to the noise present in the data and the construction of pseudo resistivity sections are the natural steps to continuing the work.

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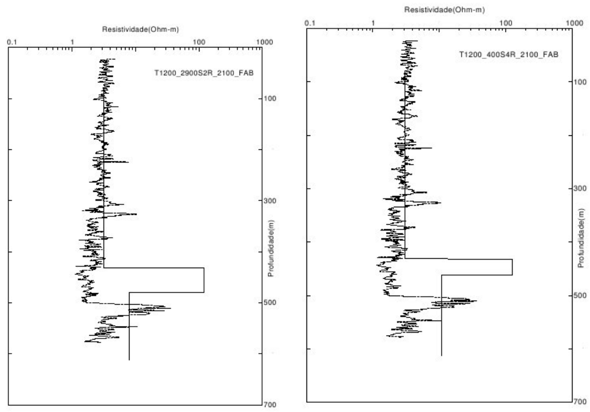

Figure 2: Comparison between the calculated resistivity and the well logs. Notice the pull up effect.

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